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Radiation Control Aspects of the Civil Construction for a High Power Free Electron Laser (FEL) Facility[1]

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The paper discusses some of the assumptions and methods employed for the control of ionizing radiation in the specifications for the civil construction of a planned free electron laser facility based on a 200 MeV, 5 mA superconducting recirculation electron accelerator. Consideration is given firstly to the way in which the underlying building configuration and siting aspects were optimized on the basis of the early assumptions of beam loss and radiation goals. The various design requirements for radiation protection are then considered, and how they were folded into an aesthetically pleasing and functional building.

INTRODUCTION

The process of achieving an architectural solution to the many and varied needs of the FEL facility, some conflicting, is beyond the scope of this paper. Some discussion is given, however, to the various approaches considered which ultimately resulted in the current design - at present under construction. It is hoped that such a discussion of the radiation protection aspects will illustrate the importance of including such considerations early in the design process.

The FEL facility is located on the Jefferson Laboratory[2] (JL) site inside the racetrack shaped tract defined by the Continuous Beam Accelerator (CEBA).

ACCELERATOR DESIGN AND BEAM LOSS

A detailed description of the FEL accelerator is given by Neil [1]. Before radiological considerations could be incorporated into the building design, a layout of the equipment in the accelerator vault was needed (see floor plan). Also needed was an estimate of expected average beam loss conditions, and also any maximum beam loss excursion that could occur under fault conditions, and the radiation design criterion for personnel exposure.

Of primary concern was shielding for the prompt radiation that arises principally from the routinely expected beam loss as a consequence of normal accelerator operations:

(a) All accelerators will give rise to prompt radiation during operation, due to inefficiencies in confining the beam to the design orbit. The physics behind this loss mechanism is complex and depends on the type of accelerator and charged particles. The loss mechanisms include gas scattering and gas interactions, quantum effects such as synchrotron radiation production, charge transfer injection, space charge interactions, beam break up and wake field effects, and emittance dilution due to intrinsic errors in the accelerating structure and magnet optics.

(b) Beam loss also results from deliberate, but small, spills for the purpose of conducting beam-physics studies to improve or upgrade the accelerator performance or to study and verify the integrity of the various installed safety systems.

(c) Beam loss can also occur due to occasional failure of beamline optical elements or the acceleration system.

(d) Operators of the accelerator and beam transport optics occasionally miss-tune the apparatus or attempt to transport a beam that is inconsistent with the intended aperture.

(e) Beam loss also occurs by design in order to use the beams for an end product - in this case to generate synchrotron radiation.

The design of shielding for accelerators is usually based on an estimate of normal beam loss from routine operations, such as described above. This results in a source term of some fraction of the total beam power, typically 0.1% or as low as 0.01% in a few cases. For major beam loss regions, such as collimators and beam dumps, the shielding will be designed typically for 100% of beam power.

Taking all the above considerations into account we assumed a beam loss for the machine at the 0.1% level. Because this loss is considered to be too conservative as a continuous single point loss anywhere around the machine we averaged this total in time and position by using a line source term.

With regard to the maximum possible beam loss, one could superficially argue that because the maximum power of the beam is given by 200 MeV and a maximum mean current of 5 mA, i.e., 1 MW, then the maximum possible loss will be 1 MW. However, because of energy recovery the actual maximum loss will be less than 100 kW which is the same as the installed RF power of the klystrons.

In addition to providing a shielded vault for the accelerator, an area for the experimental program with the laser beams and also a location for the klystrons and power supplies and other services was required.

JL DESIGN CRITERIA FOR RADIATION

Most institutions require a radiation design goal which results in a proper level of protection for workers and the general public. This goal is generally set well below regulatory limits and also might take into account the type

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[2] The Thomas Jefferson National Accelerator Facility (previously the Continuous Electron Beam Accelerator Facility - CEBAF) is informally called the Jefferson Laboratory (JL). The existing accelerator on the JL site is still referred to as CEBA.

of exposed population, the frequency of the exposure and location where the exposure occurs. Also considered is the likely location of people when the accelerator is operating and when it is down for maintenance. A further factor in the design goal is that the major portion of the annual worker dose usually arises from maintenance on activated components when the machine is down. Therefore, to increase the annual worker dose from prompt radiation by economizing on shielding might not be cost effective in the long run.

The JL design goal of 250 mrem (2.5 mSv) per calendar year (or approximately 0.1 mrem (1 μSv) per hour for a work year) is unlikely to result in a worker dose increment greater than about 100 mrem (1 mSv) per calendar year when all other dose reduction factors mentioned above operate.

For the protection of the general public, JL has a design goal for prompt radiation of 10 mrem per calendar year at the fence line.

With regard to the discharge of activated air, any accelerator produced radioactive nuclides are usually of short life and are of relatively low toxicity. Therefore, accelerator facilities are usually able to maintain radiation exposures from activated air to any critical off-site population to below the 0.1 mrem (1 μSv) per calendar year criterion for monitoring requirements set by the EPA [2].

The creation of activated material in any groundwater surrounding an accelerator and the subsequent transport of the radioactivity off-site is not a significant source of radiation exposure. Indeed, it has been stated in the literature that there has been no observation of any significant groundwater system contamination from any accelerator operation [3]. However, because of public concerns, JL is being held to a groundwater standard based on water sampled from wells close to the accelerator building. Measured radioactivity attributable to accelerator operations should be less than 25% of the standard for community drinking water [4].

CIVIL ENGINEERING CONSIDERATIONS

At the very basic level, civil considerations for all projects are identical; the resulting facility must meet operational and aesthetic needs, be economically maintainable for the desired life span, and be affordable. For the FEL, there were certain non radiological considerations that are not routinely encountered.

(a) Rigidity was desired between the accelerator area and the experimentation area to provide permanency to the FEL beam optical transmission.

(b) Considering a site-wide water table averaging approximately 6 feet below grade, deep excavation was undesirable due to added cost and construction time, and life cycle problems associated with submerged structures.

(c) Tests simulating construction activities had indicated that even marginally heavy impacts to the earth would create vibrations sufficient to disrupt operation of the accelerating cavities of the CEBA. Relocation of the FEL outside the existing accelerator ring markedly increased costs due to the unavailability of utilities and potentially enlarged the radiation fence line perimeter. Projected accelerator operating schedules did not permit construction during "down" periods.

The added challenge, then, indicated the appropriate facility would be one within the existing accelerator ring for proximity to utilities, built as a monolith for operational stability, and placed at a grade that would provide adequate but economical radiation shielding while limiting below-grade development to the extent possible. Added restraints dealt with the somewhat limited size of the site available within the accelerator ring, and the known ground vibration restrictions.

From a civil design viewpoint, all of the above constraints posed little problem if the radiation concern had not been present - merely build a rigid box structure at grade level. The necessity for economical shielding led to a different initial approach. In particular, the level of shielding required in the azimuthal plane for the intense end-on bremsstrahlung spike strongly indicated natural earth as the most cost effective medium in this area.

The initial design located the accelerator vault totally below grade to get the most economical azimuthal shielding using the surrounding earth. A thick concrete slab ceiling provided vertical shielding and served as a foundation for the experimental hall. The structure was designed as a monolith. Drawbacks included the cost of de-watering and excavation and dramatically increased projected vibratory problems. These were especially bothersome as the excavation time overlapped badly with any scenario of projected accelerator run schedules. Further, the deeper the excavation became, the closer the activity approached the geological formation (Upper Yorktown) that the existing accelerator tunnel rests on. Conflict was inevitable.

A second proposal considered a purely above-ground installation. This would have simplified construction (from the sub-grade viewpoint), but the massive side wall thickness required for azimuthal shielding proved expensive. The stacked (laboratory-over-accelerator) scheme envisioned in the initial idea was rejected for aesthetic considerations, and the laboratory was placed beside the accelerator area. This introduced additional problems: having to either provide otherwise unnecessary roof thickness to shield from skyshine radiation and providing a monolithic structure with a footprint doubled in size. The added size of the footprint also proved difficult to fit into the available site.

A third proposal - and the one which proved most satisfactory - was a variation of the initial stacked idea with side shielding provided by berming the partially buried accelerator vault. The roof of the accelerator vault was modified to become a concrete box structure with only that amount of concrete required for structural integrity, and sand fill to act as shielding. (A comparable thickness was used based on the density ratio of sand to concrete.)

The floor of the resulting structure is below the water table - but only to a level requiring surface pit de-watering for construction. This scheme also permitted an almost perfect match between the amount of excavated material and berm material - and since the geological data indicated the earth to be excavated is suitable berm material, an additional saving was realized.

Once the basic structure was decided upon using assumed shielding requirements, it was used as a template to determine the exact thickness required - whether earth, concrete, concrete-with-sand fill, or a concrete and earth combination. In the final analysis, the earth berms as initially proposed provided more than adequate azimuthal shielding at any angle of elevation.

Considerable architectural and civil engineering effort was required to transform the spaces as identified into a functional building. Much of this effort surrounded the need to satisfy functional and safety code required accesses, and to provide safely shielded ducts for wave-guides, cabling, ventilation, etc. Consideration was also given to providing minimum wall thickness for achieving ground water protection standards. In all of these endeavors, it proved important and cost effective for the radiation specialist to work closely with the architect. This close cooperation during the early developmental stages enabled the architect to provide the radiation specialist with sectional drawings through proposed features such as stairwells, penetrations and access ways. Adequate shielding could then be incorporated easily in these difficult areas from the outset, avoiding the cost and time associated with design revisions at the Title II level.

RADIATION ANALYSIS OF BUILDING

Accelerator vault top shielding

As mentioned in an earlier section of this note, the cost of this item was minimized by the use of a concrete box structure filled with sand. The sizing was based on lateral neutron and photon source terms from published data [5-7]. The neutron data was checked using the Monte Carlo transport codes MARS12 [8] and GEANT [9] with neutron event generators based on PICA [10] and DINREG [11]. Photon data was compared with the results using EGS4 [12] and MARS12. The results showed that the photon and neutron dose rates were approximately the same. The photon dose rate is strongly influenced by the size and shape of the object struck by the beam, and for specific loss points quite modest amounts of lead or iron local shielding can be very effective. Therefore, although allowance was made for the contribution from photon radiation much more effort was taken to specify neutron source terms and neutron transport. The appropriate thickness of the vault ceiling (laboratory floor) was 7.25 feet (equivalent concrete).

East wall and east access labyrinth

This aspect of the final design is of particular interest because of the need to provide rather thick walls to shield against the very penetrating forward bremsstrahlung spike and also to provide an adequate access labyrinth without compromising the shield thickness. Furthermore, because this part of the building is the main access, it is necessary to take into account the problems of radiation transmission up stairwells and lift shafts. A number of oblique sections had to be studied to ensure that all possible rays to occupied areas had been considered. The overall thickness of the East wall was 11.5 feet (concrete). This thick shield wall permitted the architect to install a very effective access labyrinth with four legs.

South-west wall to service vault and emergency exit

This was not considered so critical as the East end because of infrequent use (low occupancy) of the service area. The thickness of equivalent concrete was specified at approximately 9 feet and at the emergency exit, 10 feet.

Wave guide penetrations, and other ducts

The penetrations needed in the shielding for wave-guides, cables and air ducts represented potential weaknesses. The wave-guide penetrations, 7 in number, seemed the most significant channels for radiation transmission. The radiation transmission of the penetration was studied using MARS12 with the PICA spectrum modified by extending, by hand, the spectrum from 15 MeV (PICA's cut-off) down to 0.1 MeV. The design was done in conjunction with the RF engineer and architect to minimize cost and problems of wave-guide installation. The result was a simple rectangular section penetration with two right angle bends which included a removable plug which could, if necessary, be replaced partially by a steel insert.

Ground water requirements

Numerous studies of groundwater activation by accelerator radiation indicate that the only radionuclides of concern are tritium and sodium-22. Both of these nuclides will migrate in water and have quite long half lives. Production cross sections for both these radionuclides in soils have been published [13], and other experimental determinations (unpublished) have been made on the actual site soils. Use of these data and the estimated neutron fluence rates show that the building will meet the standards set for JL [4].

Control of activated air

Detailed calculations on the environmental impact of activated air were not considered necessary at this stage. Estimates based on equilibrium production rates indicated that maximum levels within the vault under assumed beam loss conditions would only approach one DAC. On the basis of experience at other accelerators this amount of activated air would not be of any environmental consequence. Furthermore, the ventilation system has been designed in a way that prevents significant release of air during operation thus reducing the radioactive air release rate to negligible proportions.

CONCLUSIONS

The free electron laser civil construction project represents a successful design process - which the authors confidently believe will result in a successful facility. As discussed in this paper, the facility needs were clearly specified and any potentially awkward aspects identified early on and, most importantly, the design process was controlled from the outset to accommodate these features at an early stage.

Radiation protection of people was the most prominent non-standard design requirement. While this paper deals with only part of the totality of requirements needed for effective radiation control - necessary items such as access control, installed monitors, training and staffing and also the very important laser safety studies which will need to be carried out for the experimental area have not been discussed - it does point out and demonstrate how effective collaborative efforts across widely differing specialist skills can result in a successful product.

The resulting design, illustrated below, has passed the final pre-construction hurdle by successfully undergoing a formal review by radiation and accelerator specialists.

ACKNOWLEDGMENTS

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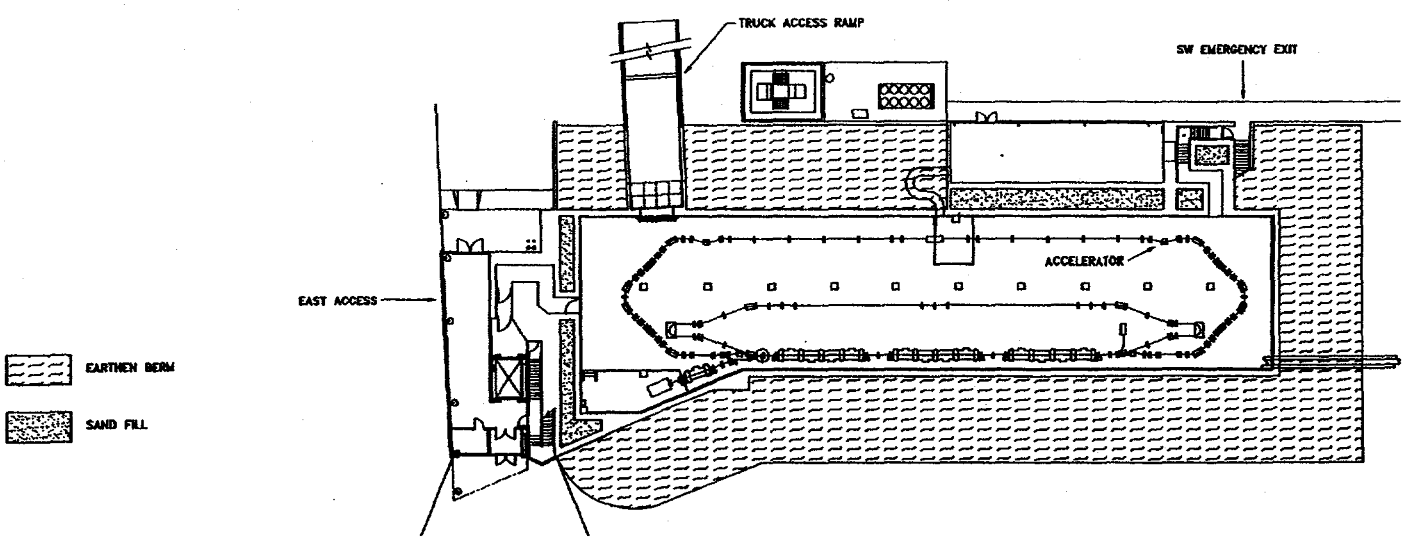
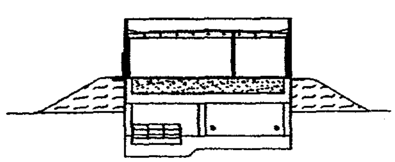
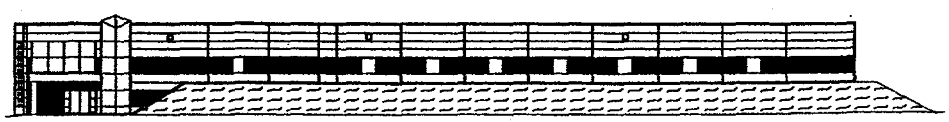
FEL Building as Designed



FIRST FLOOR PLAN



BUILDING SECTION



NORTH ELEVATION